

**NANOLAYERED COATED CUTTING TOOL
AND METHOD FOR MAKING THE SAME**

FIELD OF THE INVENTION

The invention pertains to a multi-layered
5 coated cutting tool and a method for making the same.
More particularly, the invention pertains to a
nanolayered coated cutting tool and a method for making
the same. In this regard, a nanolayered coated cutting
tool has a coating scheme that comprises adjacent
10 coating nanolayers having thicknesses of about 100
nanometers or less.

BACKGROUND OF THE INVENTION

Multi-layered coated cutting tools
demonstrate excellent metalcutting properties in
15 certain circumstances. Typically, a multi-layered
coated cutting tool comprises a substrate with a
plurality of coating layers deposited thereon. In some
cases the coating layers comprise a plurality of sets
of alternating coating layers. In this regard, U.S.
20 Patent No. 6,103,357 to Selinder et al. for a
MULTILAYERED COATED CUTTING TOOL shows a multi-layered
non-repetitive coating scheme in which the layers have
a thickness that ranges between 0.1 to 30 nanometers.
PCT Patent Application WO98/44163 to Sj strand et al.
25 for a MULTILAYERED COATED CUTTING TOOL shows a multi-
layered repetitive coating scheme in which each repeat
period has a thickness that ranges between 3 and 100
nanometers.

Other exemplary coating schemes comprise
30 multi-layered titanium nitride/titanium aluminum
nitride coatings deposited by physical vapor deposition
(PVD) techniques. Such coating schemes are described
in Hsieh et al., "Deposition and Characterization of

TiAlN and multi-layered TiN/TiAlN coatings using unbalanced magnetron sputtering", Surface and Coatings Technology 108-109 (1998) pages 132-137 and Andersen et al., "Deposition, microstructure and mechanical and 5 tribological properties of magnetron sputtered TiN/TiAlN multilayers", Surface and Coatings Technology 123 (2000) pages 219-226.

Even though multi-layered titanium nitride/titanium aluminum nitride coating schemes 10 exist, for a coating to be effective it must possess a certain minimum adhesion to the substrate and it must exhibit a certain minimum hardness. It has always been, and still remains, a goal to improve the adhesion of the coating to the substrate of the coated cutting 15 tool. In addition, it has always been, and still remains, a goal to optimize the hardness of the coated cutting tool. It has always been, and still remains, a goal to improve and optimize the combination of the properties of adhesion and hardness for a coated 20 cutting tool.

It would thus be desirable to provide a coated cutting tool (e.g., a nanolayered coated cutting tool), as well as a method for making the coated cutting tool, wherein the cutting tool possesses 25 improved adhesion and optimized hardness, as well as an improvement in the combination of the adhesion and hardness.

It would also be desirable to provide a metal nitride/metal aluminum nitride coated cutting tool 30 (e.g., a nanolayered titanium nitride/titanium aluminum nitride coated cutting tool), as well as a method for making the coated cutting tool, wherein the cutting tool possesses improved adhesion and optimized hardness, as well as an improvement in the combination 35 of the adhesion and hardness.

It would also be desirable to provide a metal aluminum nitride/metal aluminum carbonitride coated cutting tool (e.g., a nanolayered titanium aluminum nitride/titanium aluminum carbonitride coated cutting 5 tool), as well as a method for making the coated cutting tool, wherein the cutting tool possesses improved adhesion and optimized hardness, as well as an improvement in the combination of the adhesion and hardness.

10 It would also be desirable to provide a metal nitride/metal aluminum nitride/metal aluminum carbonitride coated cutting tool (e.g., a nanolayered titanium nitride/titanium aluminum nitride/metal aluminum carbonitride coated cutting tool), as well as 15 a method for making the coated cutting tool, wherein the cutting tool possesses improved adhesion and optimized hardness, as well as an improvement in the combination of the adhesion and hardness.

SUMMARY OF THE INVENTION

20 In one form, the invention is a nanolayered coated member that comprises a substrate that has a surface and a coating on the surface of the substrate. The coating comprises a plurality of coating sets of nanolayers wherein a set comprises alternating 25 nanolayers of a nanolayer of a metal nitride (wherein the metal nitride may optionally include carbon and/or silicon) and a nanolayer of a metal aluminum nitride (wherein the metal aluminum nitride may optionally include carbon and/or silicon). The coating includes a 30 bonding region and an outer region. The bonding region comprises a plurality of the coating sets wherein the thickness of a coating set generally increases as one moves away from the surface of the substrate. The outer region comprises a plurality of the coating sets.

The metal may comprise titanium, niobium, hafnium, vanadium, tantalum, zirconium and/or chromium alone or in combination with each other or in combination with other metals including aluminum in the metal nitride 5 layer so long as the composition of the metal nitride layer differs from that of the metal aluminum nitride layer.

In another form, the invention is a nanolayered coated member that comprises a substrate 10 that has a surface and a coating on the surface of the substrate. The coating comprises a plurality of coating sets of nanolayers wherein a set comprises alternating nanolayers of a nanolayer of a metal aluminum nitride (wherein the metal aluminum nitride 15 may optionally include carbon and/or silicon) and a nanolayer of a metal aluminum carbonitride (wherein the metal aluminum carbonitride may optionally include silicon). The coating includes a bonding region and an outer region. The bonding region comprises a plurality 20 of the coating sets wherein the thickness of a coating set generally increases as one moves away from the surface of the substrate. The outer region comprises a plurality of the coating sets. The metal may comprise titanium, niobium, hafnium, vanadium, tantalum, 25 zirconium and/or chromium alone or in combination with each other or in combination with other metals.

In yet another form, the invention is a nanolayered coated member that comprises a substrate that has a surface and a coating on the surface of the 30 substrate. The coating comprises a plurality of coating sets of nanolayers wherein a set comprises alternating nanolayers of a nanolayer of a metal nitride (wherein the metal nitride may optionally include carbon and/or silicon), a nanolayer of a metal 35 aluminum nitride (wherein the metal aluminum nitride

may optionally include carbon and/or silicon), and a nanolayer of a metal aluminum carbonitride (wherein the metal aluminum carbonitride may optionally include silicon). The coating includes a bonding region and an 5 outer region. The bonding region comprises a plurality of the coating sets wherein the thickness of a coating set generally increases as one moves away from the surface of the substrate. The outer region comprises a plurality of the coating sets. The metal may comprise 10 titanium, niobium, hafnium, vanadium, tantalum, zirconium and/or chromium alone or in combination with each other or in combination with other metals including aluminum in the metal nitride layer so long as the composition of the metal nitride layer differs 15 from that of the metal aluminum nitride layer and metal aluminum carbonitride layer.

In still another form thereof, the invention is a process for making a nanolayered coated member, the process comprising the steps of: providing a 20 substrate having a surface; providing a metal target (wherein the metal target may optionally include carbon and/or silicon); providing a metal-aluminum target (wherein the metal-aluminum target may optionally include carbon and/or silicon); rotating a substrate 25 between the metal target and the metal-aluminum target; supplying electrical power at a first level of electrical power to the metal target; supplying electrical power at the first level to the metal-aluminum target; depositing a coating comprising 30 coating sets of alternating nanolayers on the surface of the substrate; changing the deposition rate of the alternating nanolayers over a selected period of time during which electrical power supplied to the metal target changes from the first level to a second level; 35 and controlling the deposition rate of the alternating

nanolayers for a period of time after the electrical power reaches the second level. The metal may comprise titanium, niobium, hafnium, vanadium, tantalum, zirconium and/or chromium alone or in combination with 5 each other or in combination with other metals including aluminum in the metal target so long as the composition of the metal target differs from that of the metal-aluminum target.

In still another form thereof, the invention 10 is a process for making a nanolayered coated member, the process comprising the steps of: providing a substrate having a surface; providing a metal-aluminum target (wherein the metal-aluminum target may optionally include carbon and/or silicon); providing a 15 metal-aluminum-carbon target (wherein the metal-aluminum-carbon target may optionally include silicon); rotating a substrate between the metal-aluminum target and the metal-aluminum-carbon target; supplying electrical power at a first level to the metal-aluminum 20 target; supplying electrical power at the first level to the metal-aluminum-carbon target; depositing a coating comprising coating sets of alternating nanolayers on the surface of the substrate; changing the deposition rate of the alternating nanolayers over 25 a selected period of time during which electrical power supplied to the metal-aluminum target and the metal-aluminum-carbon target changes from the first level to a second level; and controlling the deposition rate of the alternating nanolayers for a period of time after 30 the electrical power reaches the second level. The metal may comprise titanium, niobium, hafnium, vanadium, tantalum, zirconium and/or chromium alone or in combination with each other or in combination with other metals.

In still another form thereof, the invention is a process for making a nanolayered coated member, the process comprising the steps of: providing a substrate having a surface; providing a metal target (wherein the metal target may optionally include carbon and/or silicon); providing a metal-aluminum target (wherein the metal-aluminum target may optionally include carbon and/or silicon); providing a metal-aluminum-carbon target (wherein the metal-aluminum-carbon target may optionally include silicon); rotating a substrate between the metal target and the metal-aluminum target and the metal-aluminum-carbon target; supplying electrical power at a first level to the metal target; supplying electrical power at the first level to the metal-aluminum target; supplying electrical power at the first level to the metal-aluminum-carbon target; depositing a coating comprising coating sets of alternating nanolayers on the surface of the substrate; changing the deposition rate of the alternating nanolayers over a selected period of time during which electrical power supplied to the metal target and to the metal-aluminum target and to the metal-aluminum-carbon target changes from the first level to a second level; and controlling the deposition rate of the alternating nanolayers for a period of time after the electrical power reaches the second level. The metal may comprise titanium, niobium, hafnium, vanadium, tantalum, zirconium and/or chromium alone or in combination with each other or in combination with other metals including aluminum in the metal target so long as the composition of the metal target differs from that of the metal-aluminum target and the metal-aluminum-carbon target.

BRIEF DESCRIPTION OF THE DRAWINGS

The following is a brief description of the drawings that form a part of this patent application:

5 FIG. 1 is an isometric view of a specific embodiment of a nanolayered coated cutting tool;

10 FIG. 2 is schematic cross-sectional view of a cutting edge of the nanolayered coated cutting tool of FIG. 1 showing the substrate with the nanolayered coating comprising a bonding region and an outer region, and also including a finishing layer and a lubricious layer;

15 FIG. 3 is a photomicrograph taken via transmission electron microscopy (TEM) technique of the interface between the coating and the substrate for the nanolayered coated cutting tool of Example 276;

FIG. 4 is a photomicrograph taken via transmission electron microscopy (TEM) technique of the mid-section of the coating for the nanolayered coated cutting tool of Example 276; and

20 FIG. 5 is a photomicrograph taken via transmission electron microscopy (TEM) technique of the surface region of the coating for the nanolayered coated cutting tool of Example 276.

DETAILED DESCRIPTION

25 Referring to the drawings, FIG. 1 illustrates a specific embodiment of a cutting tool generally designated as 20. Cutting tool 20 has a top rake surface 22 and flank surfaces 24. The top rake surface 22 intersects with the flank surfaces 24 so as to form 30 cutting edges 26 at the intersections thereof.

As shown in FIG. 2, cutting tool 20 comprises a substrate 30 that has a nanolayered coating as shown by brackets 32. The nanolayered coating 32 comprises a bonding region as shown by the brackets 34 in FIG. 2.

The bonding region 34 comprises one or more coating sets of nanolayers (and typically a plurality of coating sets of nanolayers) as described hereinafter. The nanolayered coating 32 also includes an outer 5 region as shown by brackets 36 in FIG. 2. The outer region comprises a plurality of coating sets of nanolayers as described hereinafter.

FIG. 2 shows that the nanolayered coating 32 has been applied to the rake surface 38 and the flank 10 surface(s) 40 of the substrate 30. However, it should be appreciated that there are instances in which the nanolayered coating 32 may only be applied to a selected one of the surfaces or selected portions of the surfaces of the substrate.

15 Referring to one arrangement of the nanolayered coating, the nanolayered coating may comprise two or more coating sets of alternating layers of materials wherein one of the materials is a metal nitride and the other material is a metal aluminum 20 nitride (e.g., titanium nitride/titanium aluminum nitride or titanium aluminum nitride/titanium nitride). What this means is that in one specific coating scheme, the metal nitride (e.g., titanium nitride) layer may be the layer closest to (or actually on) the surface of 25 the substrate. Yet, in another specific coating scheme, the metal aluminum nitride (titanium aluminum nitride) layer may be the layer closest to (or actually on) the surface of the substrate. Applicants contemplate that metal nitrides and metal aluminum 30 nitrides of the following metals and their alloys would be acceptable for use in the nanolayered coating: titanium, niobium, hafnium, vanadium, tantalum, zirconium, and/or chromium alone or in combination with each other or in combination with other metals. The 35 metal nitride layer may include aluminum so long as the

composition of the metal nitride layer differs from that of the metal aluminum nitride layer. The metal nitride and the metal aluminum nitride each may include (as an optional component) carbon and/or silicon.

5 Still making general reference to another arrangement of the nanolayered coating, the nanolayered coating may comprise two or more coating sets of alternating layers of materials wherein one of the materials is a metal aluminum nitride and the other
10 material is a metal aluminum carbonitride (e.g., titanium aluminum nitride/titanium aluminum carbonitride or titanium aluminum carbonitride/titanium aluminum nitride). What this means is that in one specific coating scheme, the metal aluminum nitride
15 (e.g., titanium aluminum nitride) layer may be the layer closest to (or actually on) the surface of the substrate. Yet, in another specific coating scheme, the metal aluminum carbonitride (e.g., titanium aluminum carbonitride) layer may be the layer closest
20 to (or actually on) the surface of the substrate. Along the lines of the metal nitride/metal aluminum nitride coating sets, applicants contemplate that the following metals and their alloys would be acceptable for use with the nanolayered coating: titanium,
25 niobium, hafnium, vanadium, tantalum, zirconium, and/or chromium alone or in combination with each other or in combination with other metals. The metal aluminum nitride may include (as optional components) carbon and/or silicon. The metal aluminum carbonitride may
30 include (as an optional component) silicon.

Referring to still another arrangement of the nanolayered coating, the nanolayered coating may comprise alternating layers of a metal nitride, a metal aluminum nitride and a metal aluminum carbonitride.

35 Various arrangements of these nanolayers are presented

as follows when the metal is titanium: titanium nitride/titanium aluminum nitride/titanium aluminum carbonitride or titanium aluminum carbonitride/titanium aluminum nitride/titanium nitride or titanium aluminum 5 carbonitride/titanium nitride/titanium aluminum nitride or titanium aluminum nitride/titanium aluminum carbonitride/titanium nitride or titanium nitride/titanium aluminum carbonitride/titanium aluminum nitride or titanium aluminum nitride/titanium 10 nitride/titanium aluminum carbonitride.

In one group of these arrangements with titanium as the metal, the titanium nitride layer may be the layer closest to (or actually on) the surface of the substrate. In this group, the titanium aluminum 15 nitride layer and the titanium aluminum carbonitride layer are the other layers.

In another group of these arrangements, the titanium aluminum nitride layer may be the layer closest to (or actually on) the surface of the 20 substrate. In this group, the titanium nitride layer and the titanium aluminum carbonitride layer are the other layers.

In still another group of the arrangements, the titanium aluminum carbonitride layer may be the 25 layer closest to (or actually on) the surface of the substrate. In this group, the titanium nitride layer and the titanium aluminum nitride layer are the other layers.

Although the specific compounds for the 30 coating arrangements set forth above are titanium nitride, titanium aluminum nitride and titanium aluminum carbonitride, applicants contemplate that other metal nitrides, metal aluminum nitrides and metal aluminum carbonitrides would be acceptable. In this 35 regard, other metals and their alloys for the metal

nitride, the metal aluminum nitride, and the metal aluminum carbonitride include niobium, hafnium, vanadium, tantalum, zirconium, and/or chromium alone or in combination with each other or in combination with 5 other metals. The metal nitride layer may include aluminum so long as the composition of the metal nitride layer differs from the composition of the metal aluminum nitride layer and the metal aluminum carbonitride layer. In the above arrangements, the 10 metal nitride (e.g., titanium nitride) and the metal aluminum nitride (e.g. titanium aluminum nitride) each may (as an option) include carbon and/or silicon. The metal aluminum carbonitride (e.g., titanium aluminum carbonitride) may as an optimal component include 15 silicon.

Referring back to the specific coating scheme shown in FIG. 2, the bonding region 34 comprises a plurality of coating sets of alternating nanolayers of titanium nitride and titanium aluminum nitride. The 20 purpose of the bonding region is to provide good adhesion between the coating and the substrate during usage (e.g., metalcutting applications). The bonding region has a thickness that ranges between about .025 micrometers and about 0.6 micrometers. More 25 preferably, the bonding region has a thickness than ranges between about 0.05 micrometers and about 0.4 micrometers. Each nanolayer in the bonding region (whether it is a nanolayer of titanium nitride or a nanolayer of titanium aluminum nitride) has a thickness 30 that may range between about 0.5 nanometers and about 5 nanometers, and more preferably, may range between about 0.5 nanometers and about 2 nanometers.

The thickness of the titanium aluminum nitride layer is typically different than the thickness 35 of the titanium nitride layer. Generally speaking, the

thickness of a coating layer varies due to one or more factors where in these factors are set out below without limitation.

5 The coating sets that comprise the bonding region are deposited during the so-called "ramp up" portion of the coating process. The "ramp up" portion of the process occurs during the initial part of the process in which the deposition rate is increased from a first level to a second level. Although it depends 10 upon the time to complete the so-called "ramp up" portion of the process, the number of coating sets of layers may extend into the hundreds since each coating set has a thickness in the nanometer range (i.e., a thickness of less than about 100 nanometers).

15 As a result of this continuing increase in the deposition rate during the ramp up period, the thickness of the coating sets in the bonding region changes. More specifically, it is generally the case that as one moves away from the surface of the 20 substrate, the thickness of each coating set increases (typically gradually) until the thickness of each coating set reaches a point at which the coating sets exhibit a generally consistent thickness. In the process, the deposition rate increases during the ramp 25 up period, which results in the increase in thickness. The increase in deposition may be due to (without limitation) any one or more of the following factors: the gas composition in the chamber, the gas flow rate in the chamber, the sputtering rate of the target 30 and/or the level of electrical power supplied to the target.

It should be appreciated that the increase in the thickness of each coating set may be due to each of the nanolayers increasing in thickness. As an 35 alternative, the increase in the thickness of each

coating set may occur when the thickness of one nanolayer remains substantially constant and the thickness of the other nanolayer increases.

In the process, for example, once the 5 electrical power to the targets reaches the second level of electrical power, the electrical power preferably will be reduced for at least one of the targets to a level greater than the first level of electrical power for the remainder of the coating 10 process to apply the outer region. The reduced level of electrical power may be different for each target. Also, the level of electrical power applied to each target may vary during the portion of the process to apply the outer region.

15 Referring to the bonding region, for example, the titanium nitride layer and the titanium carbonitride layer may include an aluminum content ranging from 0 to a higher level so long as the amount of aluminum is less than that contained in the titanium 20 aluminum nitride layers and in the titanium aluminum carbonitride layers.

Still referring to FIG. 2, the plurality of coating sets that comprise the outer region are alternating nanolayers of titanium nitride and titanium 25 aluminum nitride. The outer region has a thickness that ranges between about 1 micrometer and about 20 micrometers so long as there is good adhesion between the coating and the substrate in metalworking applications. More preferably, the outer region has a 30 thickness that ranges between about 1 micrometer and about 10 micrometers. Each nanolayer (whether it is titanium nitride or titanium aluminum nitride) has a thickness that may range between about 0.5 nanometers and about 20 nanometers. More preferably, the 35 thickness of each such nanolayer ranges between about

0.5 nanometers and about 10 nanometers. Most preferably, the thickness of each such nanolayer ranges between about 0.5 nanometers and about 2 nanometers.

The thickness of each coating set in the 5 outer region may be substantially equal or the thicknesses may vary. In the situations in which the coating sets have a substantially equal thickness, the thickness of the nanolayers that make up the coating 10 set, i.e., titanium nitride nanolayer and the titanium aluminum nitride nanolayer, may not necessarily be equal. In fact, as will be seen from the description hereinafter of the coating scheme in FIG. 3, the thickness of the titanium nitride nanolayer ranges between about 1 nanometer to about 2 nanometers and the 15 thickness of the titanium aluminum nitride nanolayer ranges between about 10 nanometers to about 11 nanometers. In this regard, the thickness of the titanium nitride nanolayers in the bonding region also range between about 1 nanometer to about 2 nanometers. 20 while the thickness of the titanium aluminum nitride nanolayers increase as the coating sets move away from the substrate. Applicants contemplate that the titanium nitride nanolayer can preferably range in thickness between about 0.5 to about 2 nanometers. 25 Applicants also contemplate that the titanium aluminum nitride nanolayer can preferably range in thickness between about 0.5 to about 11 nanometers.

As mentioned above, because the sputtering rate for the titanium-aluminum target is greater than 30 the sputtering rate for the titanium target, generally speaking, the thickness of each nanolayer of titanium aluminum nitride may be greater than the thickness of each nanolayer of titanium nitride.

Referring to FIG. 2, layer 50 is a finishing 35 layer that may comprise titanium nitride or titanium

aluminum nitride. The thickness of finishing layer 50 is between about 0.1 micrometers and about 3 micrometer. Applicants contemplate that metal nitrides, metal aluminum nitrides and metal aluminum 5 carbonitrides would be acceptable as the finishing layer. In this regard, other metals and their alloys for the metal nitride, the metal aluminum nitride, and the metal aluminum carbonitride include titanium, niobium, hafnium, vanadium, tantalum, zirconium, and/or 10 chromium alone or in combination with each other or in combination with other metals. The finishing layer alternately or in addition to the above finishing layers may be an alumina layer. The finishing layer is typically applied by physical vapor deposition (PVD) 15 techniques. Layer 52 is a lubricious layer that may comprise a material like molybdenum disulfide. The total thickness of finishing layer 50 and lubricious layer 52 is between about 0.1 micrometer and about 3 micrometers. The finishing layer and the lubricious 20 layer are each optional layers for the coating scheme.

Still referring to FIG. 2, the substrate 30 is typically a hard material such as cemented carbide.

One exemplary composition for the substrate 30, which is substrate A, is a cemented (cobalt) tungsten carbide 25 material that has up to 0.1 weight percent tantalum, up to 0.1 weight percent niobium, up to 0.1 weight percent titanium, between about 0.3 and about 0.5 weight percent chromium, between about 5.7 weight percent and 6.3 weight percent cobalt with the balance being 30 tungsten and carbon wherein most of the tungsten and carbide is in the form of tungsten carbide. The substrate has a hardness between about 92.6 and about 93.4 Rockwell A, a coercive force (H_c) of between about 250 and about 320 oersteds, a specific gravity of 35 between about 14.80 and about 15.00 grams per cubic

centimeter, a tungsten carbide grain size of 1-5 micrometers, and a magnetic saturation of between 167.7 and 191.9 microTesla cubic meter per kilogram cobalt. As will be discussed hereinafter, the coated cutting 5 inserts used in the turning tests comprised a substrate of the same composition as substrate A.

Another exemplary composition for the substrate, which is substrate B, is a cemented (cobalt) tungsten carbide material that has between about 1.2 to 10 about 2.5 weight percent tantalum, between about 0.3 to about 0.6 weight percent niobium, up to 0.4 weight percent titanium, between about 11 weight percent and 12 weight percent cobalt with the balance being tungsten and carbon wherein most of the tungsten and 15 carbide is in the form of tungsten carbide. The substrate has a nominal hardness of about 89.8 Rockwell A, a coercive force (H_c) of between about 145 and about 185 oersteds, a specific gravity of between about 14.1 and about 14.5 grams per cubic centimeter, a tungsten 20 carbide grain size of 1-6 micrometers, and a magnetic saturation of between 167.7 and 187.9 microTesla cubic meter per kilogram cobalt. As will be discussed hereinafter, the coated cutting inserts used in the milling tests comprised a substrate of the same 25 composition as Substrate B.

The substrate may also be a cermet, a ceramic or a high speed steel, polycrystalline cubic boron nitride, polycrystalline diamond or diamond sheet or diamond film. The substrate may take the form of an 30 indexable cutting insert, a cutting insert, a drill, milling cutter, end mill, reamer or tap made of any of the foregoing substrate materials.

The preferred adhesion strength of the coating to the surface of the substrate is at least 45 35 kilograms (kg). More preferably, the adhesion strength

is at least 60 kg, and most preferably the adhesion strength is at least 100 kg. The test to determine the adhesion strength is a Rockwell A indentation test.

The preferable thickness of the entire 5 nanolayered coating, exclusive of a finishing layer and a lubricious layer, is between about 1 micrometers and about 21 micrometers, and more preferably the thickness is between about 1 micrometers and about 11 micrometers, and most preferably the thickness of the 10 entire nanolayered coating is between about 2 micrometers and about 6 micrometers.

Generally speaking, the process to produce the coatings comprises using a physical vapor deposition technique such as magnetron sputtering. In 15 the following examples, the apparatus used to apply the coating was a Cemecon CC800/8 magnetron sputtering coating reactor. The coating reactor was configured so that the cutting insert substrates were rotated between two sets of targets. Each set of targets was disposed 20 180° from the other set. One of the sets of targets was two targets of titanium and the other set of targets was two titanium-aluminum targets. The substrate table was rotated at a rate of 0.8 revolutions per minute. The substrates were mounted on 25 rotating planetary rod fixtures on the substrate table.

In these examples, the process comprises two basic portions. The first is the so-called "ramp up" portion which the power to the targets is increased from about 500 watts to a target power, such as, for 30 example, about 8000 watts, over the course of about 45 minutes. Once the power reached its target, then as one alternative it is adjusted so as to remain constant (which may be, for example, 8000 watts or a lower electrical power level) throughout the balance of the 35 coating process. As another option, the electrical

power may be varied during the balance of the coating process. The nature of the variation may be, for example, as a sinusoidal wave or as a square tooth wave or as a saw tooth wave.

5 The following examples were made in a fashion generally consistent with the above description of the coating process. Each of the examples in Table I includes substrates that had a composition like that of Substrate A and substrates that had a composition like 10 that of Substrate B. The titanium target was solid titanium metal. The titanium-aluminum target comprised a titanium metal target having forty-eight plugs of aluminum therein. The process parameters for each one of these examples are set forth in Table I below.

15

Table I
Process Parameters for Examples of
Titanium Nitride/Titanium Aluminum Nitride Nanolayer Coatings

Example	Ti Target Power (KW)	TiAl Target Power (KW)	Argon Flow Rate (sccm)	Nitrogen Flow Rate (sccm)	Coating Time (hours)	Bias Current (Amps)	Nitrogen Partial Flow Rate
274	4	6	175	~113	6	21	0.31
276	4	8	175	~120	6	26	0.32
277	8	4	175	~119	6	25	0.32
281	4	6	175/100	~180	6	20	0.5
418	1.6	8	210	~90	6	21	.24
422	1.6	8	210	~88	6	20	.24

20 In each one of these examples, the flow rate for the Krypton was 80 standard cubic centimeter per minute (sccm). In Table I the designation "sccm" for the argon and nitrogen flow rate is standard cubic

centimeter per minute. In Table I the nitrogen partial flow rate equals the flow rate of nitrogen (sccm) divided by the sum of the flow rates of nitrogen, argon and Krypton (sccm). For Example 281 in Table I, the 5 argon flow rate of 175 sccm existed at the start of the ramp up period and decreased during the ramp up period to a flow rate equal to 100 sccm which was maintained during the remainder of the coating process.

In the processing, there is control over the 10 aluminum content of the titanium aluminum nitride depending upon the specific metalcutting application. For some applications it is generally preferred that the aluminum/titanium atomic ratio (Al/Ti atomic ratio) is less than 1.0. In these applications, a preferred 15 range for the Al/Ti atomic ratio is between about 0.2 and about 0.9. For other applications it is generally preferred that the Al/Ti atomic ratio be greater than or equal to 1.0 wherein a preferred range for the Al/Ti atomic ratio is between 1.0 and about 2.5. The 20 limitation of the higher end range is based upon the ability of the coated cutting insert to have adequate hardness for metalcutting applications.

To increase the Al/Ti atomic ratio one may increase the level of electrical power to the aluminum- 25 containing target(s) and/or control the nitrogen partial flow rate. To obtain a maximum aluminum content with a constant electrical power to the aluminum-containing target(s), one can decrease the nitrogen partial flow rate. One preferred nitrogen 30 partial flow rate is a rate below 0.5. A more preferred nitrogen partial flow rate is a rate below 0.4. A still more preferred nitrogen partial flow rate is a rate less than 0.35. If the nitrogen partial flow rate is below 0.2, then the adhesion and hardness of

the layers decreases. Overall, the preferred range for the nitrogen partial flow rate is between 0.2 and 0.35.

Table II below sets forth the process parameters for Example 449. The ramp up for Example 5 449 was the same as for the earlier examples, except that the titanium targets were replaced by titanium-aluminum-carbon targets. Each titanium-aluminum-carbon target comprised twelve plugs of aluminum and twelve plugs of graphite in a titanium metal target.

10 Table II - Process Parameters for Example 449
(Titanium Aluminum Carbonitride/Titanium Aluminum Nitride Nanolayer Coatings)

Example	TiAlC Target Power (KW)	TiAl Target Power (KW)	Argon Flow Rate (sccm)	Nitrogen Flow Rate (sccm)	Coating Time (hours)	Bias Current (Amps)	Nitrogen Partial Flow Rate
449	8	1.6	210	87	6	15	0.23

For the processing of Example 449, the flow of Krypton gas remained constant at a rate of 80 standard cubic centimeter per minute. In Table II the designation "sccm" for the argon and nitrogen flow rate is standard cubic centimeter per minute.

Table III below sets forth the process parameters for Example 394. The ramp up for Example 20 394 was the same as that for Example 449, except that the titanium-aluminum targets were replaced by titanium targets. Each titanium-aluminum-carbon target comprised twelve plugs of aluminum and twelve plugs of graphite in a titanium metal target.

Table III – Process Parameters for Example 394
(Titanium Aluminum Carbonitride / Titanium Nitride Nanolayer Coatings)

Example	TiAlC Target Power (KW)	Ti Target Power (KW)	Argon Flow Rate (sccm)	Nitrogen Flow Rate (sccm)	Coating Time (hours)	Bias Current (Amps)	Nitrogen Partial Flow Rate
394	8	1.6	210	80	6	20	0.22

For the processing of Example 394, the flow of Krypton
5 gas remained constant at a rate of 80 milliliters per
minute. In Table III the designation "sccm" for the
argon and nitrogen flow rate is standard cubic
centimeter per minute.

10 Selected properties of the resultant coated
cutting tool are set forth in Table IV below. These
properties are the aluminum/titanium atomic ratio, the
overall thickness of the coating in micrometers, the
microhardness of the cutting tool in kilograms per
square millimeter (kg/mm^2) as measured by a standard
15 Vickers test at a 25 gram load and the indent adhesion
strength of the coated cutting tool as measured in
kilograms.

20 Referring to the analysis of the coating
layers, a JEOL 6400 Scanning Electron Microscope (SEM)
with an Oxford Industries INCA Energy 400 Dispersive
X-Ray Spectroscopy (EDS) is used to collect
compositional information about the coatings (i.e., the
titanium aluminum nitride coatings). Oxford Industries
is located at 130A Baker Avenue Ex, Concord, MA 01742
25 and JEOL USA, Inc. is located at 11 Dearborn, Peabody,
MA 01960.

The coating is analyzed in the as deposited
state with no additional sample preparation or

conductive coating applied. X-Rays are collected using a 15KV accelerating voltage.

The coating must be a minimum of about 3 micrometers in thickness to prevent the excitation of 5 the substrate by the electron beam (thicker coatings would be necessary if a higher accelerating voltage was used). A minimum of 5 spectra are collected and the results quantified. The apparent concentration of each 10 element is equal to the intensity of that element in the sample times the weight percent of that element in the standard divided by the intensity of the element in the standard. This must then be corrected for inter-element effects so that the weight percent of the 15 element is equal to the apparent concentration divided by the intensity correction. Atomic percentages are then calculated by dividing the weight percent by the atomic weight of the element. There are several methods of calculating intensity corrections. This particular analytical scheme uses a Phi-Rho-Z approach. 20 Since correction factors are dependent on the composition of the sample, true concentrations are derived using an iterative calculation.

Table IV
Selected Properties of the Examples Using Substrate A

Example	Al/Ti Atomic Ratio (%)	Thickness (μm)	Average Values of Vickers Microhardness (kg/mm ²)	Indent Adhesion Strength (kg)
274	0.6	3.4/4.1/3.4	2770 ± 101	> 60
276	0.67	3.9/4.1/3.8	3051 ± 133	> 60
277	0.25	4.1/3.9/3.6	2856 ± 071	> 60
281	0.46	3.2/2.8/2.9	2767 ± 169	> 60
418	1.1	4.5/5.6/5.3	2774 ± 32	> 60
422	1.18	3.6/3.6/4.0	2818 ± 245	> 60
394	0.24 [4.9 atomic % carbon present]	4.2/4.1/4.0	3016 ± 133	> 60
449	0.36 [2.9 atomic % carbon present]	4.4/4.2/3.9	2899 ± 60	> 60

The examples set out in Table IV used substrates that
5 had a composition like that of Substrate A. For the properties listed in Table IV, applicants expect that the coated cutting inserts using a substrate that had a composition like Substrate B would exhibit the same or substantially similar properties.

10 Some of the examples were tested in a turning application. The turning parameters were: workpiece material was 304 stainless steel, the speed was 500 surface feet per minute (sfm) [152 meters per minute], the feed was 0.012 inches per revolution (ipr) [0.3
15 millimeters per revolution], the depth of cut was 0.080 inches (d.o.c.) [2 millimeters d.o.c.], and flood coolant. The cutting tool was a CNGP432 style of cutting tool with a negative 5 degrees lead angle and a sharp cutting edge. The results of the turning tests
20 are set forth in Table III below.

The criteria for the tool life are as follows: uniform flank wear: 0.012 inches (0.3 millimeters); maximum flank wear: 0.016 inches (0.4 millimeters); nose wear: 0.016 inches (0.4 millimeters); crater wear: 0.004 inches (0.100 millimeters); chip width on rake: 0.020 inches (0.5 millimeters); and depth of cut notch: 0.016 inches (0.4 millimeters).

Table V

Example	Rep. 1	Rep. 2	Average	Std. Deviation
277	18.00	14.30	16.15	2.62
274	14.93	23.56	19.24	6.11
281	12.46	11.00	11.73	1.03
276	27.28	21.66	24.57	3.97
KC5010 [Comparative Example]	14.00	16.00	15.00	1.41

For Comparative Example KC5010, the substrate had the same composition as Substrate A. The coating was a single layer of titanium aluminum nitride with a nominal thickness of about 4.0 micrometers. Still referring to Comparative Example KC5010, the Al/Ti ratio equaled about 1.0, and the microhardness equaled about 2500 Kg/mm². The KC5010 cutting tool is a prior art cutting tool available from Kennametal Inc. of Latrobe, Pennsylvania.

Referring to the photomicrograph FIG. 3, there is shown the bonding region and the outer region of the coating scheme from Example 276. For each one of the bonding region and the outer region there are

alternating nanolayers of titanium nitride and titanium aluminum nitride. The dark nanolayers are titanium nitride and the light nanolayers are titanium aluminum nitride.

5 For FIG. 3, and also FIGS. 4 and 5, it should be appreciated that applicants believe that the visual contrast in darkness between the nanolayers shows that the titanium nitride nanolayers have no aluminum contained therein, or significantly less aluminum
10 contained therein than do the titanium aluminum nitride nanolayers. It should be appreciated that the titanium nitride nanolayers are not necessarily pure titanium nitride since they may contain aluminum. To the extent there is aluminum contained in the titanium nitride
15 nanolayers, this aluminum content may vary between the titanium nitride nanolayers. Applicants believe that the splotchy areas in the figures, and especially FIG. 3, are artifacts of TEM specimen preparation.

Referring to the bonding region, the
20 nanolayers of titanium nitride have a thickness of between about 1 to 2 nanometers. The thickness of the titanium nitride nanolayers remains substantially constant throughout the bonding region. The thickness of the titanium aluminum nitride nanolayers begins at a
25 range between about 1 to about 2 nanometers at and near the interface between the coating and the substrate. The substrate is the black area in the upper right-hand corner of the photomicrograph. The thickness of the titanium aluminum nitride layers increases as one moves
30 away from the surface of the substrate. The thickness of the titanium aluminum nitride nanolayers increases to a range between about 10 to about 11 nanometers.

Referring to the photomicrograph FIG. 4, there is shown the bulk region of the coating scheme.
35 The bulk region comprises alternating nanolayers of

titanium nitride and titanium aluminum nitride wherein one nanolayer of titanium nitride and one nanolayer of titanium aluminum nitride comprises a coating set. The thickness of each nanolayer of titanium nitride is

5 about equal and ranges between about 1 to about 2 nanometers. The thickness of each nanolayer of titanium aluminum nitride is about equal and ranges between about 10 nanometers to about 11 nanometers.

Referring to the photomicrograph FIG. 5,
10 there is shown the region of the coating scheme that includes the outer surface thereof. This region of the coating scheme comprises alternating nanolayers of titanium nitride and titanium aluminum nitride wherein one nanolayer of titanium nitride and one nanolayer of

15 titanium aluminum nitride comprises a coating set. The thickness of each nanolayer of titanium nitride is about equal and ranges between about 1 to about 2 nanometers. The thickness of each nanolayer of titanium aluminum nitride is about equal and ranges between about 10 nanometers to about 11 nanometers.

The examples were tested in a milling application. The milling parameters were: workpiece material was 4140 steel, the speed was 600 surface feet per minute (sfm) [183 meters per minute], the feed was

25 0.012 inches per revolution (ipr) [0.3 millimeters per revolution], the axial depth of cut (a.d.o.c.) was 0.100 inches [2.5 millimeters rdoc] and the radial depth of cut (r.d.o.c.) was 3.0 inches [75 millimeters rdoc], and flood coolant. The cutting tool was a

30 SEHW43A6T style of cutting tool with a 45 degree lead angle and a T land of 0.2 millimeters and 20 degrees. The results of the milling tests are set forth in Table VI below.

The criteria for the tool life are as

35 follows: uniform flank wear: 0.012 inches

(0.3 millimeters); maximum flank wear: 0.016 inches (0.4 millimeters); nose wear: 0.016 inches (0.4 millimeters); crater wear: 0.004 inches (0.100 millimeters); and chip width on rake:

5 0.030 inches (0.75 millimeters). The examples set out in Table VI used a substrate that had a composition like Substrate B. Comparative Example KC525M is a cutting tool that has a substrate with a composition like that of Substrate B and a coating of titanium

10 aluminum nitride wherein the coating has a nominal thickness of about 4 micrometers.

Table VI
Tool Life (Minutes) for Milling of 4140 Steel

Example	Rep. 1	Rep. 2	Rep. 3	Average Tool Life / Std. Deviation
277	7.45	6.62	9.10	7.72/1.26
274	7.45	8.28	8.28	8.00/0.48
281	4.96	7.45	8.28	6.90/1.73
276	8.28	4.97	8.28	7.18/1.91
KC525M [Comparative Example]	4.97	4.97	6.62	5.52/0.96

15 The patents and other documents identified herein are hereby incorporated by reference herein.

Other embodiments of the invention will be apparent to those skilled in the art from a consideration of the specification or a practice of the

20 invention disclosed herein. It is intended that the specification and examples are illustrative only and are not intended to be limiting on the scope of the invention. The true scope and spirit of the invention is indicated by the following claims.